Collaborative Problem-Solving in Mixed Reality Environments for Manufacturing Assembly Tasks

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Abstract

The rapid advancements in the digital era have transformed manufacturing training by incorporating state-of-the-art Extended Reality (XR) technologies. These immersive technologies proved to enhance training by simulating real-world scenarios, enabling trainees to develop problem-solving skills in safe and monitored environments. While most XR applications in manufacturing focus on single-user interfaces to build individual skills, collaborative training is essential for fostering teamwork and improving production efficiency. Multi-user XR platforms offer the potential to expose trainees to interdependent assembly tasks, emphasizing coordination and shared decision-making. Thus, this work explores the impact of multi-user MR training modules on manufacturing training. In prior work, our team developed an immersive single-user MR training module on hydraulic grippers that successfully demonstrated the effectiveness of MR technology for manufacturing training. Building on these promising results, we have recently upgraded the MR training module from a single-user to a multi-user experience, enabling a collaborative MR-shared environment for trainees. This study introduces the new design for the collaborative multi-user MR module. It investigates the impact of collaboration within MR-shared training settings on learning dynamics, focusing on studying task completion time and problem-solving. Studying time allows us to explore how teams effectively navigate the collaborative problem-solving process, particularly when compared to individual performance in single-user MR environments. The study involved 103 participants enrolled in a Fluid Power course, utilizing the new collaborative MR module to expose trainees to the design and assembly of a hydraulic bike. The MR-shared environment synchronizes up to four MR headsets (HoloLens 2), allowing multiple users to collaborate within the same MR scene and solve the assigned problems. This synchronized environment was developed using Microsoft Azure, a cloud computing platform, and Photon Cloud, a software service (SaaS) solution for developing multiplayer experiences. A team dynamics and collaboration assessment survey was utilized to evaluate participants' collaborative problem-solving skills, focusing on their performance. Additionally, the System Usability Scale (SUS) and Simulation Task Load Index (SIM-TLX) were integrated to assess participants' attitudes toward the tool's (MR-shared environment) usability and to explore their physical and mental workload during the assembly tasks.

Keywords: MR-shared, collaborative problem-solving, cognitive workload, manufacturing assembly, multi-user, fluid power

1. Introduction

With all the rapid technological advancements, the manufacturing industry started embracing advanced training techniques, utilizing Extended Reality (XR) technologies, from virtual reality (VR) to augmented reality (AR) and mixed reality (MR) [1]–[3]. These immersive technologies enhance manufacturing training campaigns, exposing trainees to basic manufacturing principles, particularly in design and assembly protocols, by simulating real-world problem scenarios [4],

[5]. The XR-based training in manufacturing assembly offers an effective approach, equipping the workforce with problem-solving skills in a safe, monitored XR environment [6].

XR technologies have demonstrated their potential to deliver practical assembly training by immersing trainees in XR environments that simulate real-world problems [7], [8]. The immersive environments provide a sense of presence, allowing trainees to gain the required hands-on practice experience while minimizing the risk of personal injury or equipment damage [9]. Trainees interact with virtual representations of assembly components and machinery while building muscle memory and familiarizing themselves with assembly procedures [10], [11]. Additionally, XR platforms proved to effectively communicate and reinforce standard operating procedures, ensuring consistency and adherence to best practices across the workforce. XR simulations have offered realistic equipment operation training scenarios, allowing the workforce to develop proficiency in machine setup, control, and basic troubleshooting [12]. Moreover, XR applications have proven effective in facilitating quality control training by allowing trainees to analyze complex designs, identify defects, and understand inspection criteria within a risk-free virtual environment [13].

Most of the XR applications developed for manufacturing assembly training currently focus on single-user interfaces aimed at developing individual skills [7], [8], [14]–[16]. While developing individual skill sets is essential, it is also necessary to introduce collaborative assembly training into manufacturing training campaigns. Practical training modules (traditional training) have demonstrated the benefits of collaboration among team members, highlighting the positive impact on both product quality and production efficiency [17]. Collaboration and teamwork in manufacturing training campaigns expose trainees to the interdependent nature of assembly operations by giving trainees the opportunity to coordinate and share essential information [18]. Assembly practices often require coordinated efforts from multiple workers, making collaborative skills as crucial as technical proficiency.

Given the significance of collaborative experiences in manufacturing training campaigns, researchers started integrating collaborative training XR platforms into manufacturing training programs [19]. However, the implementation of multi-user XR environments exhibits technical challenges. Research highlights issues related to the need for robust network setup to support multi-user XR interactions [20], as high-bandwidth and low-latency connections during collaborative XR training can disrupt training, leading to inconsistent user experiences and reduced training effectiveness [21]. Additionally, designing realistic collaborative scenarios poses challenges, particularly in balancing individual skill development with team-based learning objectives [22].

Despite these challenges, the potential benefits of XR-based collaborative training in manufacturing, including improved workforce capabilities and enhanced industry innovation, offer a promising platform for enhancing workforce capabilities. To this end, this current study builds on our previous research [8], which explored the impact of single-user MR training modules on manufacturing training. Expanding upon the promising results of our prior work, the current work investigates the potential of XR-shared environments (basically MR settings) to support multi-user interactions and simulated teamwork scenarios. It presents the upgradation of the MR training module from a single-user to a multi-user experience, enabling a collaborative environment for trainees. It introduces the design of this collaborative multi-user MR module, with the main objective of examining learning dynamics, focusing on task completion time and problem-solving. The new MR-shared environment design is tested with around 103 participants enrolled in a Fluid Power course, exposing them to the design and assembly of a hydraulic bike. A team dynamics and collaboration assessment survey is employed to study participants' collaborative problem-solving skills, considering performance and task completion time. Also, the System Usability Scale (SUS) and Simulation Task Load Index (SIM-TLX) are integrated to measure participants' perceptions of the MR tool's usability and explore individuals' physical and mental workload during the assembly tasks.

The rest of this paper is structured as follows. Section 2 introduces the developed MR-shared environment, including its multi-user module. This section details the upgrade from the MR-single user to the MR-shared environment, highlighting the required hardware and software integration. It also discusses the module's tasks and capabilities, emphasizing the collaborative nature of the environment and the assigned tasks. Section 3 describes the conducted research study, outlining the assessment tools used and the experimental design adopted. Section 4 presents the analysis of the collected data and discusses the findings. Finally, Section 5 concludes the study, summarizing the key outcomes.

2. Interactive MR Multi-User Module in an MR-Shared Environment

The MR multi-user module incorporates an MR-shared environment that connects up to four users, allowing them to communicate and collaborate through a seamless, synchronized network infrastructure with minimal latency. The MR-shared environment builds upon the MR-single environment developed and validated in our prior work [8], which focused on teaching manufacturing assembly protocols and demonstrated promising results.

The previous MR-single environment was designed using Microsoft's Mixed Reality Toolkit (MRTK) for Unity and deployed on the hardware HoloLens 2 [23]. It featured an interactive single-user module aimed at introducing undergraduate students to the design, assembly protocols, and mechanisms of hydraulically actuated grippers. The current MR-shared environment extends our MR-single environment by synchronizing the MR experience, transitioning from a single-user to a multi-user interface. To increase the complexity of the assigned tasks, the hydraulically actuated gripper module is replaced with an interactive MR module centered on hydraulic bike design and assembly. The following subsections present the upgrade from the MR-single to the MR-shared environment, including integrating the new MR interactive module and the associated collaborative tasks designed to explore problem-solving and learning dynamics among the team members.

2.1. Upgrading from MR-single to MR-shared environment

The diagram in Figure 1 shows the primary software/hardware integration to upgrade from the MR-single to the MR-shared environment. Recalling from our prior work [8], the MR playspace in the MR-single environment was designed using **Unity 2021.3.16**, a game engine provided by Unity Technologies [24]. Additional software, such as **SolidWorks**, **Blender**, and **Maximo**, was employed to import the 3D models along with their associated physics and virtual avatars. These models were integrated into Unity as assets to design the interactive module. The MR playspace was then structured into multiple single-user interface scenes. The **Mixed Reality Feature Tool** [25] was used to add, import, and update essential MRTK packages, including *MRTK Foundations*, *MRTK Extensions*, *MRTK Test Utilities*, and *MRTK Tools*, along with other required components for creating an interactive MR experience. For more details on the design and setup of the MR-single environment and its associated module, please refer to [8].

In the current work, this MR-single environment is upgraded into an MR-shared environment by synchronizing the MR playspace across all interactable Unity scenes, enabling real-time communication and feedback among multiple users (up to four users). The synchronization and network configuration are established using **Photon Cloud**, a software-as-a-service (SaaS) platform designed for developing multiplayer applications to enable multi-user interactions in the MR environment [26]. Photon Cloud uses the Photon Unity Networking (PUN) package, which provides the required tools to allow multiple users to interact within shared environments. The real-time collaboration is supported by **Microsoft Azure**, a cloud computing platform offering a range of capabilities for a synchronized MR experience, like *Azure Spatial Anchor, Azure PlayFab, scalable cloud storage*, etc. For instance, the *Azure Spatial Anchor*, a cloud-based service, is utilized to create persistent anchors across devices, including HoloLens 2 and PCs. This service ensures that virtual objects retain their real-world position across all the synchronized devices while supporting interactions in large physical spaces. Additionally, *Azure PlayFab* is employed to manage real-time communication, session synchronization, and user authentication, while *Azure's scalable cloud storage* is used for managing large datasets, 3D models, and assets critical for MR applications.

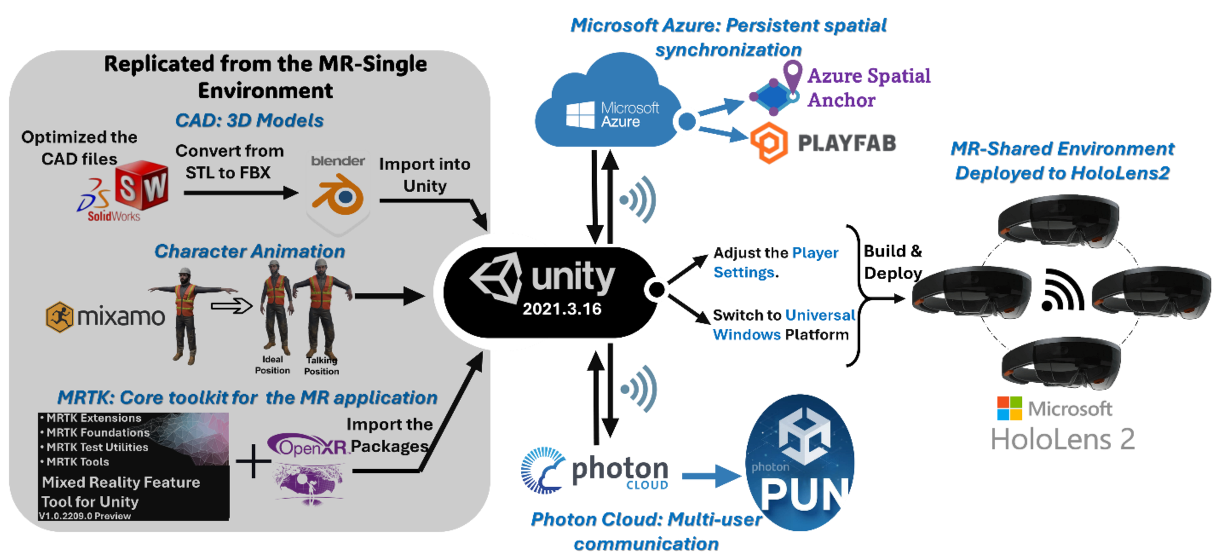

Figure 1. Diagram illustrating the basic software/hardware integration for the MR-shared environment setup.

Thus, to incorporate and utilize **Photon Cloud** and **Microsoft Azure** services for a robust MR-shared environment, the following steps are implemented. First, the *Photon Unity Networking (PUN)* package is installed and integrated into the Unity project through the Unity Package

Manager. Installing the PUN package enables the configuration of Photon Cloud services to establish a room-based architecture, allowing users to join shared sessions and interact within the MR environment. The PUN package includes **C#** scripts that are edited and customized based on the module's main tasks (e.g., assembly, operation, etc.) to manage the synchronization of object states, user interactions, and network events. This ensures real-time collaboration within the MR-shared environment.

After integrating the PUN package, *Azure Spatial Anchors* is set up to enable persistent spatial mapping across the devices used. These anchors ensure that virtual objects retain their real-world positions across multiple devices, providing a consistent and synchronized experience. Alongside Spatial Anchors, *Azure PlayFab* is implemented to handle session synchronization, real-time communication, and user authentication, creating a seamless multi-user interaction framework.

After all the required Photon and Azure packages are installed and configured, the PUN scripts are edited, and the modules are programmed based on their assigned tasks. Each scene is then tested in Unity's Play Mode to validate user actions, object states, and communication protocol synchronization. Once, the MR-shared environment is validated, it is deployed to HoloLens 2 devices using Unity's Universal Windows Platform (UWP) build settings, ensuring compatibility with the device's hardware capabilities, such as spatial mapping and hand tracking.

2.2.Module Tasks and Capabilities

The MR module within the MR-shared environment exposes users to the design and assembly of a hydraulic-actuated bike. These systems are selected given their complex mechanical design, hydraulic circuit, and operation. The hydraulic bike 3D model used for the module was originally designed by the Fluid Power Club at the School of Engineering Technology (SOET) in 2022 [27].

The module includes two sessions: (1) Tutorial Session and (2) Manufacturing Lab, both of which are collaborative and capable of connecting up to four users. The tutorial session is designed to familiarize users with the MR-shared environment, introducing the teams to various interactions and specific UI controls. It also provides an opportunity for users to understand and coordinate with each other's actions before moving to the main assembly tasks in the manufacturing lab session. Following the tutorial session, the manufacturing lab session engages teams in completing a series of tasks designed to expose them to different assembly procedures within the context of manufacturing processes. The following subsections illustrate the basic tasks involved in both the tutorial and manufacturing lab sessions.

2.2.1. Tutorial Session Tasks

The tutorial session aims to introduce the teams to the principles of spatial interactions in an MR-shared environment for performing the assigned assembly tasks. It is divided into two collaborative tasks (**Task One: Object Manipulation** and **Task Two: Control Techniques**), as illustrated in Figure 2. Both tasks require users per team to collaborate and assist each other within the MR-shared environment to successfully accomplish the tasks.

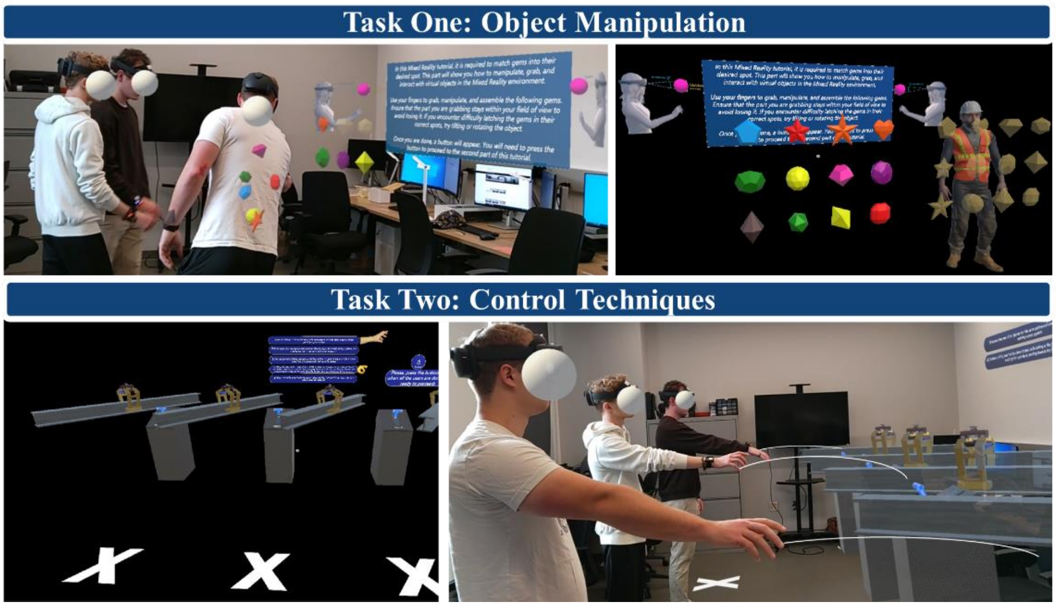

Figure 2. Two tutorial tasks in the MR-shared environment.

Task one introduces the team, consisting of three to four users, to object manipulation techniques within the MR-shared framework by assembling virtual components, represented here as gems. Each team member participates in manipulating and assembling these virtual objects using actions such as grabbing, pointing, rotating, and scaling. Users are asked to assist and help each other when facing issues, allowing the team to develop the required manipulation skills in a collaborative setting for the subsequent section. Instructional guidelines are provided through hand gestures and voice commands, enhancing the usability of the process. Successfully completing this task equips the team with the skills necessary for the manufacturing assembly section.

Task two focuses on exposing the team to the basic control techniques, including near and far manipulation protocols. Users per team interact with the virtual objects at varying distances while adapting to different user postures like standing, sitting, or reaching in the MR-shared environment. This task allows the team to collectively learn how to utilize virtual UI controls, like push buttons, sliders, and joystick, to remotely operate mechanical systems. For example, each user per team works to control a gripper's end-effector to lift a virtual I-beam from a distance. Each user contributes to the task by employing far manipulation techniques to control their own gripper while assisting teammates in operating theirs, fostering collaborative problem-solving and skill development. Throughout task two, detailed step-by-step instructions are provided via a virtual avatar, voice commands, and visual displays. The avatar, equipped with body and hand gestures, allows to maintain student engagement by providing a visually and audibly interactive guide. The use of an interactive avatar helps direct students' attention, ensuring they remain focused on the learning process. Additionally, the instructions are non-skippable, meaning students must follow them in sequence before progressing to the next step. This structured delivery method prevents students from bypassing important instructional content, reinforcing their understanding and guiding them through each phase of the task effectively. Furthermore, presenting information through multiple modalities, like visual, auditory, and interactive, enhances accessibility, addressing the students' diverse learning styles and improving overall comprehension.

For instance, one of the task instructions, delivered through voice commands and animated text displayed on a virtual screen, guides team members to extend their hand and point it at the virtual joystick. This action enables them to emit a ray with a hollow circle from their hand, allowing for precise interaction with the virtual environment. The users then collaboratively align the ray with the joystick, perform a designated hand gesture to grab it, and secure their control as indicated by the ray changing to a solid circle. The team then moves the joystick to operate the gripper, resulting in lifting the virtual I-beam. The collaborative nature of this task allows users to observe and support each other's performance, reinforcing teamwork and enabling successful task completion.

2.2.2. Manufacturing Lab Tasks

The manufacturing lab session consists of three tasks (see Figure 3, Figure 4, and Figure 5) centered on assembling the hydraulic bike, which is composed of four interdependent subsystems: Subsystem 1: Back-Upper Assembly, Subsystem 2: Front-Lower Assembly, Subsystem 3: Back-Lower Assembly, and Subsystem 4: the Bike Frame. The three tasks are as follows: **Task One: Assembly of Subsystems 1 and 2**, **Task Two: Assembly of Subsystems 3 and 4**, and **Task Three: Assembly of the Entire Bike**.

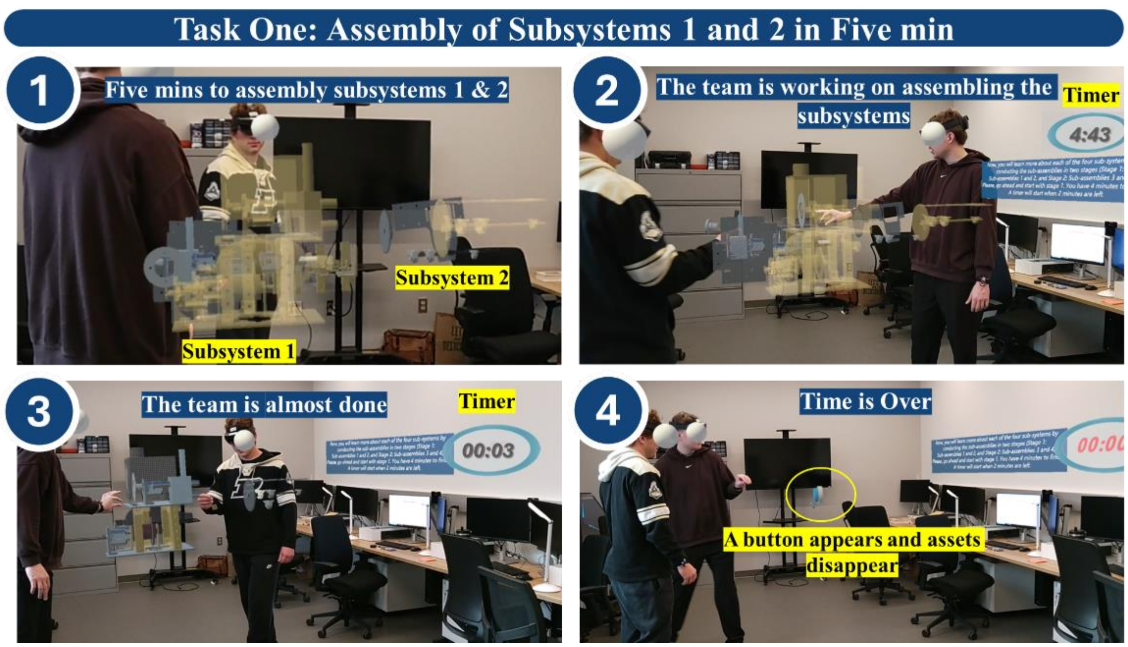

Figure 3. One team consisting of two users completing task one of the manufacturing lab session.

Task one, illustrated in Figure 3, requires team members to collaborate on assembling the first two subsystems of the bike within a **five-minute** time frame. The first two subsystems of the bike, i.e., subsystems 1 and 2, are, respectively, the tank-accumulator assembly and gearbox assembly. The tank-accumulator assembly involves the main hydraulic components such as hydraulic motors, pumps, the accumulator, the manifold, and the oil tank, which are the core of the bike's hydraulic system. The gearbox assembly involves the mechanical components required for speed variation. Each of the two subsystems contains around 20 to 25 individual components. Thus, users per team must assist one another in understanding these subsystems' structure and assembly process to successfully complete the task within the allotted time. During this task, the virtual avatar provides instructions while informing the team about the time constraints and offering hints about the assembly procedure. A timer is displayed to track progress, encouraging users to brainstorm and work efficiently. The goal of adding time constraints allows us to explore how teams collaborate under pressure, i.e., whether time constraints enhance or hinder teamwork. Visual aids, spatial sounds, and voice commands are utilized to enhance the user experience and support task completion. For example, when the time is over, a beep sound plays, and the timer changes color to red, alerting about the end of the task. Then, the virtual assets disappear as time is over, and a "Proceed" push button appears, allowing the team to move on to the next task.

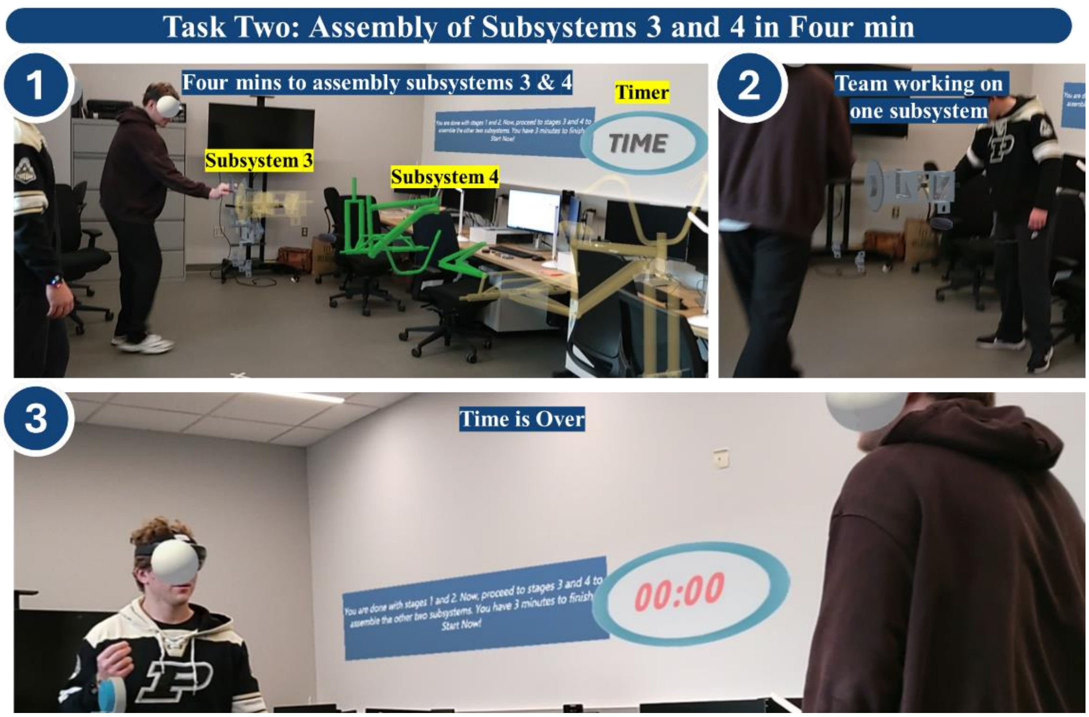

Figure 4. One team completing task two of the manufacturing lab session.

Task two starts right after the team completes the assembly of subsystems 1 and 2 in task one, regardless of whether the task was finished on time. In this second task, shown in Figure 4, the team must collaborate to assemble the other two subsystems, i.e., subsystems 3 and 4, which are, respectively, the clutch assembly and the frame assembly, within a four-minute time frame. These subsystems are comparatively less complex than the first two, making the reduced time allocation sufficient for completion. The clutch assembly includes components responsible for transferring power and managing engagement between the gearbox and the drivetrain. The frame assembly involves the structural components that hold the bike together and provide support for the other subsystems. Despite the fact that these subsystems are less intricate, they still require focus and teamwork to ensure proper assembly. Similar to task one, team members must communicate effectively and assist each other in understanding the structure and assembly process of the subsystems to meet the time constraints. Also, visual aids, spatial sounds, and voice commands are provided throughout the task to support the team. Similar to task one, a beep sound plays to alert the team that the task has ended when the time is over.

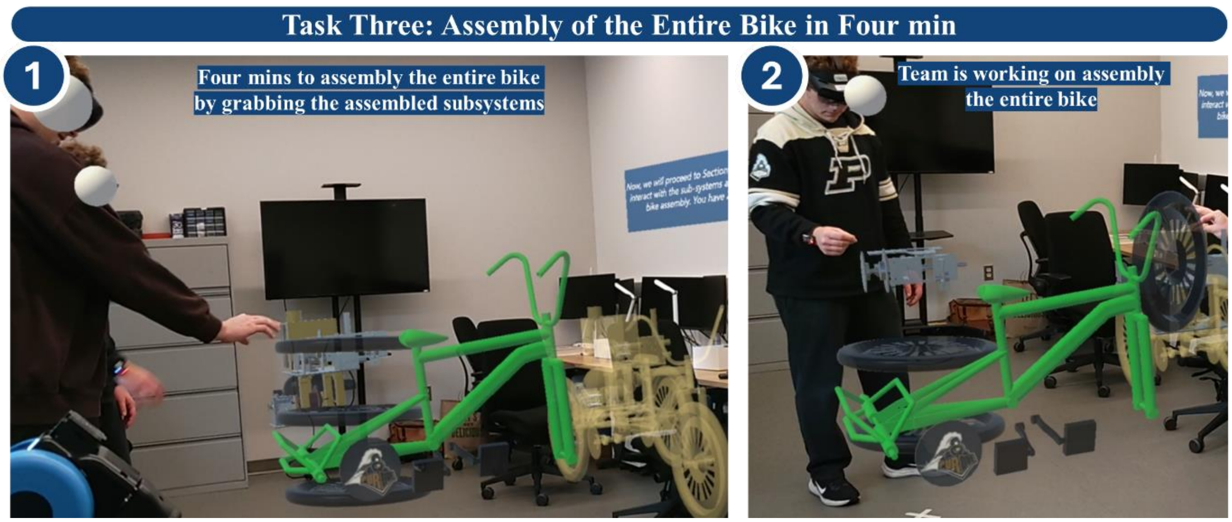

Figure 5. One team completing task three of the manufacturing lab session.

Task three, shown in Figure 5**,** serves as the final stage, where the team is directed to assemble the entire bike within a four-minute time frame. Throughout this task, the team integrates the subsystems assembled during tasks one and two while incorporating additional components such as wheels, cranks, and other structural parts to complete the assembly process. Teamwork and coordination are essential in this task, as users must collaboratively interact with the previously assembled subsystems and remaining components. Each team member plays a role in grabbing, positioning, and attaching the item, requiring synchronized efforts to achieve the task within the allocated time. Similar to the previous tasks, a visible timer is displayed, allowing users to monitor their progress and manage their time effectively while working on the assembly. Visual aids, spatial sounds, and voice commands continue to assist the team throughout this task. Thus, as in previous tasks, when the allocated time is up, a beep sound plays, alerting the team to the end of the session. The completed virtual bike assembly appears at the end of the task as a final product, providing immediate feedback on the missing components.

3. Research Study

The MR-shared environment, with its collaborative module, is incorporated in the syllabus of MET 230: Fluid Power course, where a research study is conducted. An institutional review board (IRB) application is prepared and approved (Approval Number: IRB-2024-1403) to conduct the study with the 103 students (6 females & 97 males) registered in the course.

3.1. Assessment Tools

Quantitative assessment tools, including SUS and SIM-TLX are integrated to measure students' perceptions of the MR tool's usability and explore individuals' physical and mental workload during the assembly tasks. Also, a team dynamics and collaboration assessment survey is employed to study students' problem-solving skills considering performance and task completion time. Additionally, a brief demographic survey is designed to gather information about students' backgrounds, including age, ethnicity, major, and their prior experience and familiarity with MR technology, before engaging with the module. The following subsections provide a detailed overview of the SUS, SIM-TLX, and team dynamics assessment tools.

3.1.1. The SUS Survey

The SUS survey consists of 10 standardized questions rated on a 5-point Likert scale ranging from "Strongly Disagree" to "Strongly Agree" (see Table 1) developed by John Brooke in 1986 to measure users' perceptions of the usability of any system or tool [28]. For our study, the SUS survey is utilized to assess the ease of use, efficiency, and intuitiveness of the MR module. Besides measuring the usability of the MR module, the SUS survey helps identify potential challenges or areas of improvement that might impact user interaction. For instance, it allows the exploration of potential issues related to navigation, functionality, or the clarity of user interfaces.

Table 1. SUS Survey Questions

Q1 SUS Survey Questions		Anchors of the Scale
Q1.1	I think I would like to use this tool frequently.	1= Strongly Disagree 2= Somewhat Disagree 3= Neutral 4= Somewhat Agree 5= Strongly Agree
Q1.2	I needed to learn a lot of things before I could get going with this tool.	
Q1.3	I found the tool unnecessarily complex.	
Q1.4	I thought the tool was easy to use.	
Q1.5	I think that I would need the support of a technical person to be able to use this system.	
Q1.6	I found the various functions in this tool were well integrated.	
Q1.7	I thought there was too much inconsistency in this tool.	
Q1.8	I would imagine that most people would learn to use this tool very quickly.	
Q1.9	I found the tool very cumbersome to use.	
Q1.10	I felt very confident using the tool.	

3.1.2. The SIM-TLX Survey

The SIM-TLX survey, adapted from the NASA-TLX survey, is widely used for assessing users' cognitive workload during task performance in simulated environments [29]. It consisted of 10 questions rated on a 5-point Likert scale ranging from "Very Low" to "Very High" (see Table 2) to evaluate workload across dimensions such as mental demand, physical demand, temporal demand, effort, performance, and frustration. For this study, the SIM-TLX survey is used to measure the cognitive and physical demands faced by the students while collaborating on completing the assigned tasks within the MR-shared environment. Participants rate their workload using the 5-point standardized scale, indicating the impact of the MR module on their ability to focus, manage tasks, and collaborate effectively. The results aim to identify potential stressors or challenges within the MR environment, enabling improvements to enhance user experience and task efficiency.

Table 2. The SIM-TLX Survey

Q2 SIM-TLX Survey Questions		Anchors of the Scale
Q2.1	Mental demands—How mentally fatiguing was the task?	1= Very Low 2= Low 3= Moderate 4= High 5= Very High
Q2.2	Presence—How immersed/present did you feel in the task?	
Q2.3	Physical demands—How physically fatiguing was the task?	
Q2.4	Temporal demands—How hurried or rushed did you feel during the task?	
Q2.5	Frustration—How insecure, discouraged, irritated, stressed or annoyed were you?	
Q2.6	Task complexity—How complex was the task?	
Q2.7	Situational stress—How stressed did you feel while performing the task?	
Q2.8	Distraction—How distracting was the task environment?	
Q2.9	Perceptual strain—How uncomfortable/irritating were the visual and auditory aspects of the task?	
Q2.10	Task control—How difficult was the task to control/navigate?	

3.1.3. Team Dynamics and Collaboration

Besides the SUS and SIM-TLX assessment tools, the team dynamics and collaboration survey designed and validated in [30] is used to assess various aspects of the team's functionality, collaboration, and dynamics. The survey consists of 42 questions, shown in Table 3, which aims to measure critical dimensions of team performance and interaction within the MR-shared environment. The survey evaluates areas such as task understanding, role clarity, communication effectiveness, problem-solving, adaptability, and trust within the team. For instance, it involves questions that explore team members' understanding of their roles and responsibilities, their ability to share information, and their effectiveness in collaborating on the assigned tasks. Additionally, the survey collects data on the team's capacity to foster a positive work environment, resolve conflicts, and adapt to dynamic roles during collaborative activities. The students' feedback collected through the survey helps refine the design of collaborative tasks and supports the development of strategies to enhance team performance in shared MR environments.

Table 3. Team Dynamics and Collaboration Survey

Q3 Team Dynamics and Collaboration Survey Questions		Anchors of the Scale
Q3.1	My team have general ideas of specific team tasks	1= Very Low 2= Low 3= Moderate 4= High 5= Very High
Q3.2	My team does what they are assigned to do	
Q3.3	My team knows the relationship between various task components	
Q3.4	My team looks for different interpretations of a problem when seeking a solution to various task problems	
Q3.5	My team evaluates their limitations in performing their tasks	
Q3.6	My team has a shared goal for various project tasks	
Q3.7	My team discusses its goal and attains the agreement of teammates	
Q3.8	My team knows specific strategies for completing various tasks	
Q3.9	My team knows the general process involved in conducting a given task	
Q3.10	My team understands that they have the skills necessary for doing various team tasks	
Q3.11	My team communicates with other teammates while performing team tasks	
Q3.12	My team supports continuous improvement in terms of personal skills as well as in terms of overall team skills	

Q3.13	My team defines its communications channels at the start of various team tasks	
Q3.14	My team uses a common vocabulary in task discussions	
Q3.15	My team informally communicates with one another throughout various team tasks	
Q3.16	My team consistently demonstrates effective listening skills	
Q3.17	My team likes to do various team tasks	
Q3.18	My team encourages each other's work in order to improve various team tasks outcomes	
Q3.19	My team takes pride in their work	
Q3.20	My team enjoys thinking	
Q3.21	There are no ethical problems within my team that teammates are unable to resolve	
Q3.22	My team shares information and individual team members do not keep information to themselves	
Q3.23	My team is committed to the team goal	
Q3.24	Everybody in my team strives to express his or her opinion	
Q3.25	My team understands their roles and responsibilities for doing various team tasks	
Q3.26	My team understands where they can get information for doing various team tasks	
Q3.27	My team understands their interaction patterns	
Q3.28	My team informs each other about different work issues	
Q3.29	My team is likely to make a decision together	
Q3.30	My team can flexibly adapt to any role within the team for carrying out various team tasks	
Q3.31	My team undertakes interdependent tasks	
Q3.32	My team understands how they can exchange information for doing various team tasks	
Q3.33	My team solves problems that occur while doing various team tasks	
Q3.34	There is an atmosphere of trust in my team	
Q3.35	My team creates a work environment that promotes productive results	
Q3.36	My team creates a safe environment to openly discuss any issue related to the team's success	
Q3.37	My team acknowledges and rewards behaviors that contribute to an open team climate	
Q3.38	My team often utilizes different opinions for the sake of obtaining optimal outcomes	
Q3.39	Discussions for decision-making occur within my team during meetings so that team meetings are viewed as useful activities	
Q3.40	My team has a positive team climate	
Q3.41	My team has the right experience so that a critical mass of experienced people is available on the team	
Q3.42	My team knows the environmental constraints when they perform various team tasks	

3.2.Experimental Design

The 103 students registered in the MET 230 Fluid Power course are divided into seven lab sessions, each consisting of 15 to 16 students, with each lab session allocated a total of two hours. The entire MR module takes approximately 25 to 30 minutes, and the MR-shared environment is capable of connecting and synchronizing up to four users. However, due to the limited number of headsets, teams of two to three students are formed, and the study is conducted for two consecutive weeks in multiple experiments in Lambertus Hall (LMBS) Room 4258 (see Figure 6).

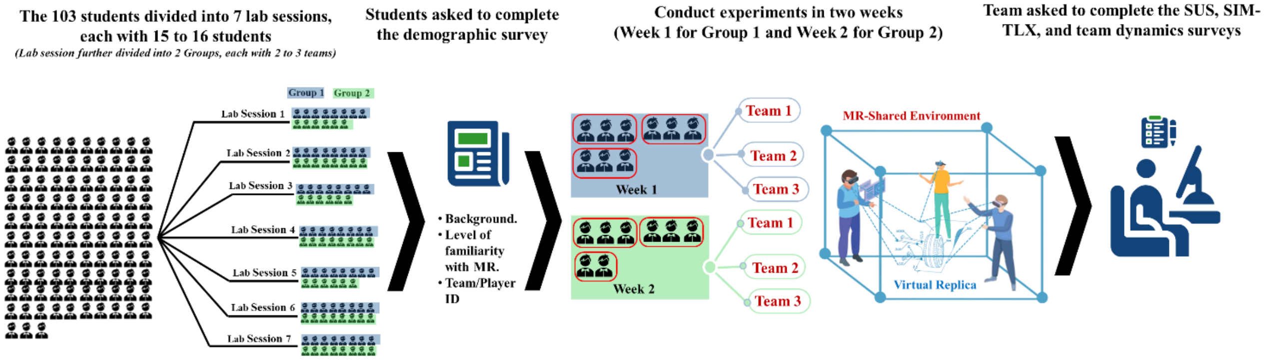

Figure 6. Diagram illustrating the experimental design of the study.

The 15 to 16 students in each lab session are further split into two groups, Group 1 and Group 2, with each group consisting of two to three teams (8 to 9 students per group). During week 1, three experiments are conducted for Group 1 in each of the seven lab sessions, allowing three teams to experience the MR-shared environment. In week 2, the remaining experiments are conducted with the rest of the teams in Group 2. For each experiment (involving a team of two to three students), all team members are first asked to complete the brief demographic survey, which collects information about their background, level of experience with MR, team number, and player ID within the MR-shared environment. Then, they are immersed in the MR-shared environment to work together on completing the assigned tasks. Six HoloLens 2 MR headsets are utilized in the study, with two to three being used per experiment, while the remaining are charged for subsequent experiments.

Once a team finishes the MR module, its members are asked to complete the post-survey, consisting of the SUS, SIM-TLX, and team dynamics and collaboration survey. As one team completes the post-survey, the next team prepares to complete the demographic survey and experience the module. This alternating process ensures that all the teams have the opportunity to engage with the module. The same procedure is applied consistently across all the teams in both groups (Group 1 and Group 2) in all seven lab sessions, ensuring comprehensive participation while managing the study and data collection. After two weeks of data collection, the quantitative data are cleaned and sorted to be ready for analysis and evaluation.

4. Data Analysis

The MR-shared environment is experienced by 103 students; however, after data collection, only 96 to 98 students fully completed all the surveys. 98 students completed the SUS and SIM-TLX surveys, while 96 students completed the team dynamics and collaboration Survey. The responses are then analyzed using a descriptive statistical approach, the computation of mean and standard deviation metrics. The following subsections present the results of descriptive analysis.

4.1. SUS Survey

The results of the students' responses to the SUS survey, aimed at assessing the usability of the MR module, are reported in Table 4 and Figure 7. Table 4 shows that questions Q1.4 and Q1.8 got the highest mean values, with **(M =4.03, SD = 0.91) for Q1.4** and **(M =4.44, SD = 0.67) for Q1.8.** The students' responses to these questions indicate that 80% (78 out of 98 students) for **Q1.4** and 94% (92 out of 98 students) for **Q1.8** rated their agreement between "Somewhat Agree" and "Strongly Agree", as illustrated in Figure 7. These results demonstrate the ease of use of the MR module, as students reported being highly comfortable using the tool, despite their limited prior familiarity with the technology. Questions Q1.1, Q1.6, and Q1.10 also received high mean values, above 3.75: **Q1.1 (M =3.9, SD = 1.05)**, **Q1.6 (M =3.82, SD = 0.77)**, and **Q1.10 (M =3.85, SD = 0.91)**. These results, visualized in Figure 7, show that 73% of the students' responses (72 out of 98) to **Q1.1**, 71% (70 out of 98) to **Q1.6**, and 68% (67 out of 98) to **Q1.10** ranged between "Somewhat Agree" and "Strongly Agree". This further validates the usability of the tool, as the majority of students (over 60%) expressed interest in using this tool for future courses, citing its well-integrated features.

Table 4. Mean and standard deviation of the SUS survey questions

SUS Survey (Completed by 98 students)	Strongly Disagree	Strongly Agree	M (Mean)	SD (Standard Deviation)
Q1.1 I think would like to use this tool frequently.	1	5	3.9	1.05
Q1.2 I needed to learn a lot of things before I could get going with this tool.	1	5	1.82	0.97
Q1.3 I found the tool unnecessarily complex.	1	5	1.8	0.82
Q1.4 I thought the tool was easy to use.	1	5	4.03	0.91
Q1.5 I think that I would need the support of a technical person to be able to use this system.	1	5	2.19	1.15
Q1.6 I found the various functions in this tool were well integrated.	1	5	3.82	0.77
Q1.7 I thought there was too much inconsistency in this tool.	1	5	2.68	1.10
Q1.8 I would imagine that most people would learn to use this tool very quickly.	1	5	4.44	0.67
Q1.9 I found the tool very cumbersome to use.	1	5	2.09	0.95
Q1.10 I felt very confident using the tool.	1	5	3.85	0.91

On the other hand, questions Q1.2 and Q1.3 received the lowest mean values, with **(M =1.82, SD = 0.97) for Q1.2** and **(M =1.8, SD = 0.82) for Q1.3,** indicating that the MR tool was perceived as straightforward and easy to use, even for individuals with little to no experience with MR technology. This is further illustrated in Figure 7, which shows that 81% of the students (79 out of 98) responded with "Somewhat Disagree" and "Strongly Disagree" to **Q1.2 and Q1.3**, both of which addressed the complexity of the tool. These responses confirm that the tool was not found to be complicated. Similarly, the rest of the questions, i.e., questions Q1.5, Q1.7, and Q1.9, received low mean values, below 3: **Q1.5 (M =2.19, SD = 1.15)**, **Q1.7 (M =2.68, SD = 1.10)**, and **Q1.9 (M =2.09, SD = 0.95)**, further confirming the usability and ease of the tool, as shown in Figure 7.

Based on the reported results of the SUS survey, the developed MR module within the MR-shared environment is usable. Most of the students (more than 65%) reported ease of use and comfort despite limited prior experience, as evidenced by high mean scores for questions related to usability and low scores for complexity, reinforcing the module's effectiveness and user-friendliness.

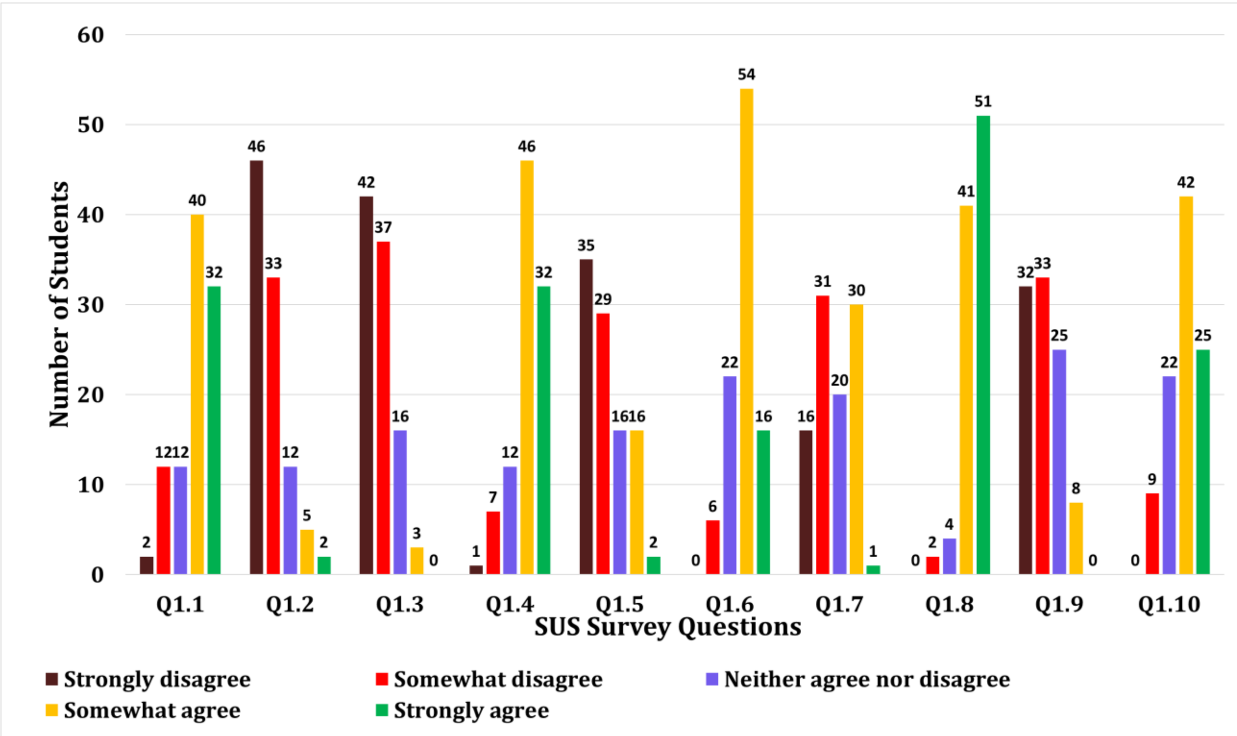

Figure 7. Statistical diagram illustrating the data collected from the students' responses the SUS survey questions.

4.2. SIM-TLX Survey

The results of the students' responses to the SIM-TLX survey, completed by 98 students, are presented in Table 5 and visualized in Figure 8. This survey was aimed at evaluating students' cognitive and physical workload while interacting with the module within the MR-shared environment. Table 5 shows that Q2.2 (Presence) received the highest mean value **(M=3.79, SD=0.86),** indicating that the majority of students felt a strong sense of presence and immersion during the task. As shown in Figure 8, 72% of the students (71 out of 98) rated their experience between "Moderate" and "Very High", reflecting the effectiveness of the MR-shared environment in creating a sense of engagement among the players (users).

On the other hand, Q2.3 (Physical Demands), Q2.7 (Situational stress), and Q2.8 (Distraction) received the lowest mean values with **(M=1.57, SD=0.69)**, **(M = 1.58, SD = 0.68)**, and **(M=1.59, SD=0.73)**, respectively. These results indicate that the tasks were neither physically demanding nor stressful or distracting, as students experienced minimal stress while performing them. As illustrated in Figure 8, the majority of the students (around 90%) rated their physical demands, situational stress, and distraction as “Very Low” or “Low”. Similarly, Q2.1 (Mental Demands) and Q2.6 (Task complexity) got low mean values **(M=1.7, SD=0.66) and (M=1.72, SD=0.70)**, respectively, indicating that more than 85% of the students (see Figure 8) reported “Very Low” or “Low” to mental demands and task complexity.

Q2.4 (Temporal demands) had a moderate mean value **(M=2.81, SD=0.79)**, with 58% of students (57 out of 98) rating their experience as “Moderate”, as shown in Figure 8. This indicates that students felt slightly hurried while completing the tasks, given the time constraints imposed during the module. Finally, Q2.10 (Task control) received the mean value (**M=2.41, SD=0.99)**, indicating that while some students found task navigation slightly challenging, the majority rated it as manageable. As shown in Figure 8, 87% of students (85 out of 98) rated task control as “Moderate” or lower.

Table 5. Mean and standard deviation of the SIM-TLX survey questions

SIM-TLX Survey (Completed by 98 students)	**Very Low**	**Very High**	**M (Mean)**	**SD (Standard Deviation)**
Q2.1 Mental demands—How mentally fatiguing was the task?	1	5	1.7	0.66
Q2.2 Presence—How immersed/present did you feel in the task?	1	5	3.79	0.86
Q2.3 Physical demands—How physically fatiguing was the task?	1	5	1.57	0.69
Q2.4 Temporal demands—How hurried or rushed did you feel during the task?	1	5	2.81	0.79
Q2.5 Frustration—How insecure, discouraged, irritated, stressed or annoyed were you?	1	5	2	0.85
Q2.6 Task complexity—How complex was the task?	1	5	1.72	0.70
Q2.7 Situational stress—How stressed did you feel while performing the task?	1	5	1.58	0.68
Q2.8 Distraction—How distracting was the task environment?	1	5	1.59	0.73
Q2.9 Perceptual strain—How uncomfortable/irritating were the visual and auditory aspects of the task?	1	5	2.12	0.98
Q2.10 Task control—How difficult was the task to control/navigate?	1	5	2.41	0.99

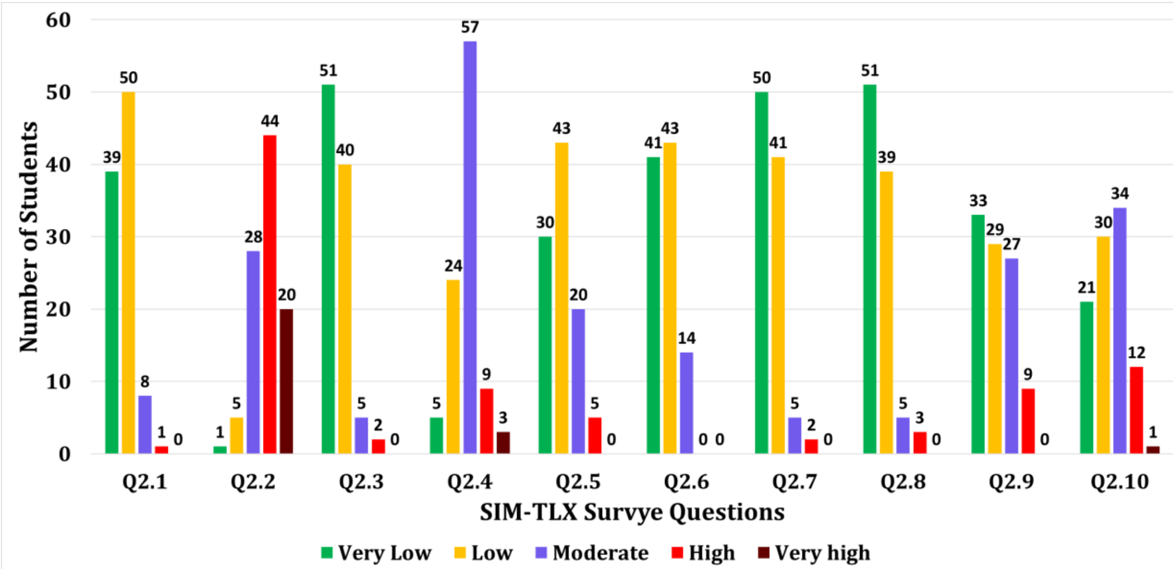

Figure 8. Statistical diagram illustrating the data collected from the students' responses the SIM-TLX survey questions.

Thus, the results from the SIM-TLX survey indicate that the MR-shared environment was neither physically nor mentally demanding, with minimal stress and frustration reported. Students felt engaged and immersed while performing the tasks, highlighting the usability and effectiveness of the MR module.

4.3. Team Dynamics Survey

The results of the team dynamics and collaboration survey, utilized to evaluate various aspects of teamwork and collaboration within the MR-shared environment, are summarized in Table 6. As shown, the results reveal positive feedback across most of the survey questions, with mean scores consistently above 4 for aspects related to team collaboration, dynamics, and problem-solving.

Table 6. Mean and standard deviation of the SIM-TLX survey questions

Team Dynamics and Collaboration Survey (Completed by 99 Students)	**Very Low**	**Very High**	**M (Mean)**	**Standard Deviation (SD)**
Q3.1 My team have general ideas of specific team tasks	1	5	4.15	0.8
Q3.2 My team does what they are assigned to do	1	5	4.39	0.64
Q3.3 My team knows the relationship between various task components	1	5	4.32	0.68
Q3.4 My team looks for different interpretations of a problem when seeking a solution to various task problems	1	5	3.98	0.85
Q3.5 My team evaluates their limitations in performing their tasks	1	5	3.75	0.94
Q3.6 My team has a shared goal for various project tasks	1	5	4.21	0.80
Q3.7 My team discusses its goal and attains the agreement of teammates	1	5	3.82	1

Q3.8 My team knows specific strategies for completing various tasks	1	5	3.91	1.01
Q3.9 My team knows the general process involved in conducting a given task	1	5	4.28	0.73
Q3.10 My team understands that they have the skills necessary for doing various team tasks	1	5	4.27	0.78
Q3.11 My team communicates with other teammates while performing team tasks	1	5	4.20	0.94
Q3.12 My team supports continuous improvement in terms of personal skills as well as in terms of overall team skills	1	5	4.21	0.80
Q3.13 My team defines its communications channels at the start of various team tasks	1	5	3.90	1.06
Q3.14 My team uses a common vocabulary in task discussions	1	5	4.32	0.8
Q3.15 My team informally communicates with one another throughout various team tasks	1	5	4.19	0.89
Q3.16 My team consistently demonstrates effective listening skills	1	5	4.28	0.73
Q3.17 My team likes to do various team tasks	1	5	4.24	0.72
Q3.18 My team encourages each other’s work in order to improve various team tasks outcomes	1	5	4.18	0.82
Q3.19 My team takes pride in their work	1	5	4.16	0.81
Q3.20 My team enjoys thinking	1	5	4.24	0.83
Q3.21 There are no ethical problems within my team that teammates are unable to resolve	1	5	4.36	0.82
Q3.22 My team shares information and individual team members do not keep information to themselves	1	5	4.29	0.71
Q3.23 My team is committed to the team goal	1	5	4.41	0.69
Q3.24 Everybody in my team strives to express his or her opinion	1	5	4.10	0.80
Q3.25 My team understands their roles and responsibilities for doing various team tasks	1	5	4.34	0.67
Q3.26 My team understands where they can get information for doing various team tasks	1	5	4.29	0.73
Q3.27 My team understands their interaction patterns	1	5	4.21	0.72
Q3.28 My team informs each other about different work issues	1	5	4.20	0.73
Q3.29 My team is likely to make a decision together	1	5	4.29	0.79
Q3.30 My team can flexibly adapt to any role within the team for carrying out various team tasks	1	5	4.25	0.71
Q3.31 My team undertakes interdependent tasks	1	5	4.27	0.74
Q3.32 My team understands how they can exchange information for doing various team tasks	1	5	4.29	0.75
Q3.33 My team solves problems that occur while doing various team tasks	1	5	4.33	0.73
Q3.34 There is an atmosphere of trust in my team	1	5	4.38	0.70
Q3.35 My team creates a work environment that promotes productive results	1	5	4.32	0.7
Q3.36 My team creates a safe environment to openly discuss any issue related to the team’s success	1	5	4.28	0.77
Q3.37 My team acknowledges and rewards behaviors that contribute to an open team climate	1	5	4.28	0.80

Q3.38 My team often utilizes different opinions for the sake of obtaining optimal outcomes	1	5	4.22	0.81
Q3.39 Discussions for decision-making occur within my team during meetings so that team meetings are viewed as useful activities	1	5	4.16	0.85
Q3.40 My team has a positive team climate	1	5	4.44	0.69
Q3.41 My team has the right experience so that a critical mass of experienced people is available on the team	1	5	4.23	0.78
Q3.42 My team knows the environmental constraints when they perform various team tasks	1	5	4.26	0.81

Questions focused on shared team goals and commitment, such as **Q3.23 (My team is committed to the team goal)** and **Q3.6 (My team has a shared goal for various project tasks)**, received high mean scores of **(M=4.41, SD=0.69)** and **(M = 4.21, SD = 0.80)**, respectively. These results indicate that students demonstrated a strong sense of dedication toward team objectives during the collaborative tasks. Other questions like **Q3.11 (My team communicates with other teammates while performing team tasks), Q3.28 (My team informs each other about different work issues),** and **Q3.29 (My team is likely to make a decision together)** related to communication effectiveness and collaboration also got high mean values. For example, **Q3.11** had a mean score of **(M=4.20, SD=0.94),** while **Q3.28** scored **(M=4.20, SD=0.73)**. Additionally, **Q3.29** received a high mean value **(M=4.29, SD=0.79)**, showcasing the collaborative decision-making process fostered by the MR-shared environment.

Questions addressing team trust and overall atmosphere also got high mean values, showing positive feedback among team members. For instance, **Q3.34 (There is an atmosphere of trust in my team)** had a mean score of **(M=4.38, SD=0.70),** while **Q3.40 (My team has a positive team climate)** recorded the highest mean score in the survey **(M=4.44, SD=0.69)**. These results prove the potential of MR technology to create a collaborative and supportive environment among team members. Questions centered on problem-solving and adaptability questions, like **Q3.33 (My team solves problems that occur while doing various team tasks)** and **Q3.30 (My team can flexibly adapt to any role within the team for carrying out various team tasks),** respectively**,** scoring **(M=4.33, SD=0.73)** and **(M=4.25, SD=0.71)**, confirms the applicability of MR to be utilized as a learning tool while promoting flexibility and effective problem-solving within teams.

Finally, the general dynamics questions assessing general collaboration dynamics, such as **Q3.1 (My team have general ideas of specific team tasks)** and **Q3.14 (My team uses a common vocabulary in task discussions)**, had mean scores of **(M=4.15, SD=0.8)** and **(M=4.32, SD=0.8)**, respectively. These results further validate the potential of the MR-shared environment in fostering a shared understanding of tasks.

The results from this survey reveal the effectiveness of the collaborative nature of the multi-user MR module in enhancing teamwork and problem-solving dynamics. The high mean scores across categories such as communication, trust, adaptability, and problem-solving indicate that the MR-shared environment effectively supports collaboration, creating a positive exciting learning experience for students. Despite being rushed by time constraints, team members adapted by assigning tasks among themselves and guiding one another, recognizing their shared objective of successfully completing the assigned tasks as a team. These results indicate that time constraints, rather than inducing stress, can also act as a catalyst for effective collaboration, encouraging team members to work together more efficiently. Additionally, the results align with the study's objectives by demonstrating that the MR module facilitates team engagement and improves learning dynamics within a shared training setting. These findings prove the potential of the developed MR-shared environment to promote cohesive teamwork besides supporting individual learning.

5. Conclusions

This study, involving 103 students enrolled in a Fluid Power course, introduced a collaborative multi-user MR module, building on our prior research to upgrade from a single-user to a multi-user MR environment. The goal was to investigate the impact of collaboration in MR environments on manufacturing training by fostering teamwork and problem-solving in a shared MR setting. The developed MR-shared environment allowed up to four users to collaborate simultaneously on the design and assembly of a hydraulic bike, providing trainees with realistic assembly scenarios in a collaborative context. A team dynamics and collaboration survey consisting of 42 items was used to evaluate the effectiveness of the MR-shared environment, assessing students' collaborative problem-solving skills and focusing on performance. Also, the SUS and SIM-TLX were employed to measure participants' perceptions of usability and explore their cognitive and physical workload during the assembly tasks. The overall results demonstrate the effectiveness of the MR-shared environment in fostering collaboration, usability, and a beneficial learning experience. Over 80% of students reported ease of use and comfort despite limited prior experience with MR technology, validating the usability of the MR module. Furthermore, the results highlight the minimal cognitive and physical workload imposed by the MR module, making it accessible and engaging for students. The team dynamics survey revealed high scores across key dimensions, such as commitment to team goals, communication effectiveness, and problem-solving, confirming the success of the MR-shared environment in promoting teamwork and collaboration.

Thus, this study shows the potential of the MR-shared environment to effectively support collaboration and teamwork in manufacturing training. High scores in problem-solving, communication, and adaptability validate the module's ability to enhance task completion and foster a deeper understanding of interdependent roles within a team. Additionally, the usability and accessibility of the MR module highlight its suitability for adoption in future training programs, making it a valuable tool for modern manufacturing education.

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